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Structural Performance of the First SSC Design B Dipole Magnet*

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ABSTRACT

The first Design B Superconducting Super Collider (SSC) dipole magnet has been successfully tested. This magnet was heavily instrumented with temperature and strain gage sensors in order to evaluate its adherence to design constraints and design calculations. The instrumentation and associated data acquisition system allowed monitoring of the magnet during cooldown, warmup, and quench testing. This paper will focus on the results obtained from structural measurements on the suspension system during normal and rapid cooldowns and during quench studies at full magnet current.

INTRODUCTION

The suspension system in a superconducting magnet performs two essential functions. First, it resists internally and externally generated structural loads imposed on the cold mass assembly ensuring that the position of that assembly is stable over the operating life of the magnet. Second, it serves to insulate the cold mass from heat conducted from the outside world.

Rigorous structural requirements combined with low allowable heat loads have resulted in a suspension system that represents a significant departure from current superconducting magnet design practice both in concept and materials selection. As a result, understanding its performance and adherence to design criteria was required early in the development process. The emphasis here is to summarize the results from the first mechanical measurements made on a full size SSC dipole in operation. The magnet used for this test is a Design B assembly, B referring to the second iteration of magnet cryostat design. The designation of this magnet is DD0014. Mechanical tests were not a routine part of the tests on early magnets simply due to the quantity of instrumentation required to perform those tests. DD0014 was the first magnet specifically designated for magnetic, thermal, and structural tests. The tests were conducted from July through September of 1988 at the Magnet Development and Test Facility at Fermilab.

SUSPENSION SYSTEM OVERVIEW

A complete review of the design and analysis involved in the current SSC suspension system is beyond the scope of the current work, but is well documented in the literature.[1,2] However, a brief overview is important in understanding its operation and the test results to be described. Fig. 1 illustrates the major cryostat components.

A complete SSC dipole magnet cryostat consists of the vacuum vessel, 80 K and 20 K shields, the cold mass, which contains the coil assembly, and the suspension system. The cold mass and shields are supported vertically and laterally at five places along their length. To accomodate axial shrinkage during cooldown, each is free to slide axially at all but the center support. The center serves as the anchor position. To distribute any axial load imposed on the cold mass to all five supports, tie bars are used to connect the top of each post to its neighbor(s). That is, any vertical or lateral load applied to the magnet is transmitted directly to the supports. An axial load is transmitted to the center post and in turn to the outboard supports through the tie bars.

COOLDOWN TEST

Cooldown restraints on magnets tested prior to DD0014 specified that the maximum temperature gradient across any single cryostat component not exceed 100 K. This constraint was a mechanism to ensure that no physical damage occur during cooldown and was viewed as a temporary measure until such time as a full mechanical test could be conducted in operation. During prototype testing, the imposed gradient limit poses no real problem save for tighter control over the refrigeration system. In production, such a constraint could severely slow the throughput of a test facility. During operation of an entire SSC accelerator, however, there is no way to provide the control over cooldown required to meet this 100 K gradient requirement. Because of this, a comparison between slow and fast cooldowns was a major goal for the test of DD0014.

Cooldown affects nearly all of the components in a cryostat assembly in some way. Structurally, three things occur which represent potential failure mechanisms. First, the 80 K and 20 K shields bow during cooldown due to asymmetry, imposing lateral loads on the support posts at their attachments. Second, axial shrinkage of the cold assembly imposes loads on the support posts due to friction between it and the slide cradles. If the breakaway friction were too high or if a slide assembly would bind, failure of one or more supports could occur. Finally, any net shrinkage of support interconnections, i.e. the tie bars, their end fittings, and the slide cradles, will decrease the post spacing at their cold end, bending the support posts.

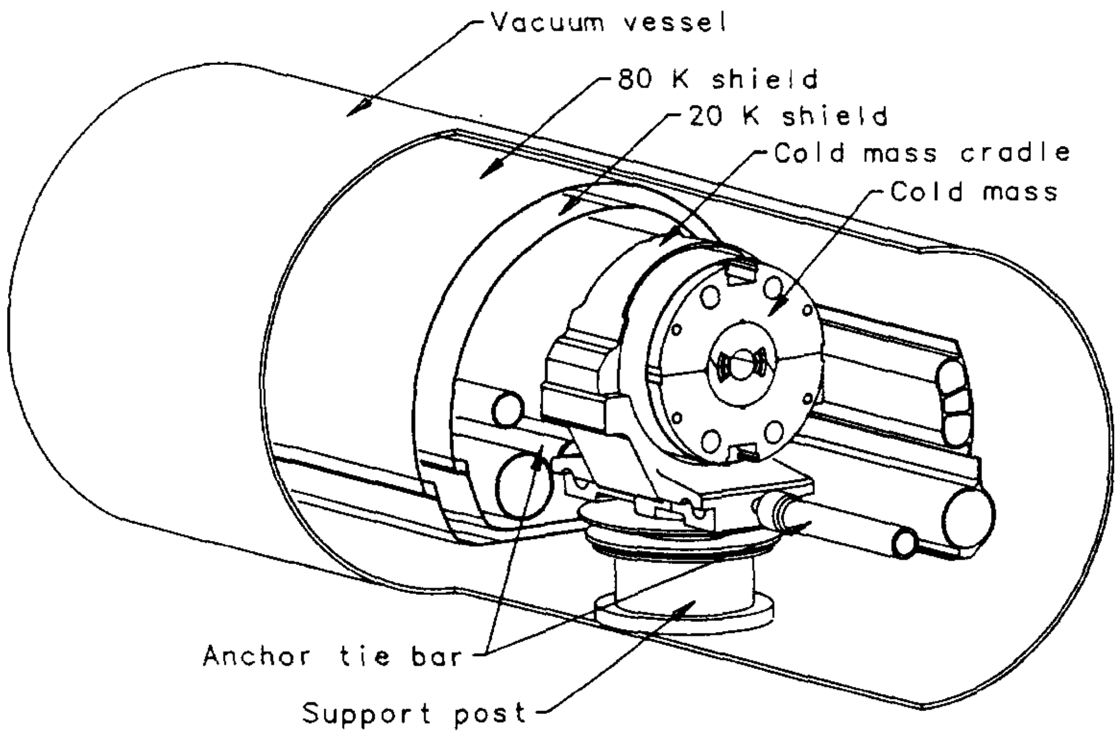

Fig. 1. Major SSC cryostat components

Early tests on the effects of shield bowing indicated that the forces generated by this motion are not sufficiently high to permanently distort the shields themselves nor to cause high bending stresses in the support posts.[3] Fig. 2 illustrates strain gage readings taken on the support posts in DD0014 during a fast cooldown resulting from bowing of the 80 K shield. It depicts a maximum lateral bending stress of 8.3 MPa (1200 psi) resulting from thermal bow.

The emphasis here is on bending stresses in the support post composite tubes acting along the long axis of the magnet. The data from two cooldowns will be presented below. The first is a normal test cooldown in which the maximum temperature gradient along the length of any cryostat component is limited by flow control to 100 K. The second cooldown represents an attempt to cool all circuits in DD0014 from room temperature to operating temperature as fast as possible. Figs. 3, 4, and 5 are plots of the temperature profiles along the length of the 80 K shield, 20 K shield, and cold mass cradles as functions of time from the start of each cooldown. They illustrate the temperatures which drive structural deformation inside the cryostat assembly.

One source of bending along the magnet axis is friction between the cradle assemblies and the cold mass skin. The bearing material is a Teflon impregnated sintered bronze on a steel backing. Tests of this material at operating temperature in vacuum yield a breakaway coefficient of friction between 0.1 and 0.25.[4] The resulting loads are not sufficient to cause high bending stresses in the supports as long as the bearings don't bind. Examination of Figs. 6 and 7 shows some evidence of sticking and slipping between the cradles and cold mass. This behavior is normal and expected. Permanent binding of a bearing pad to the cold mass would cause almost certain failure of the support system, especially if it occurred early in the cooldown cycle.

Axial shrinkage of the suspension system components drives the final source of bending in the post assemblies. For most materials this is virtually complete by the time the assembly is at 80 K which, in the case of the slow cooldown, took approximately 33 hours. For the fast cooldown it took 12 hours. The maximum

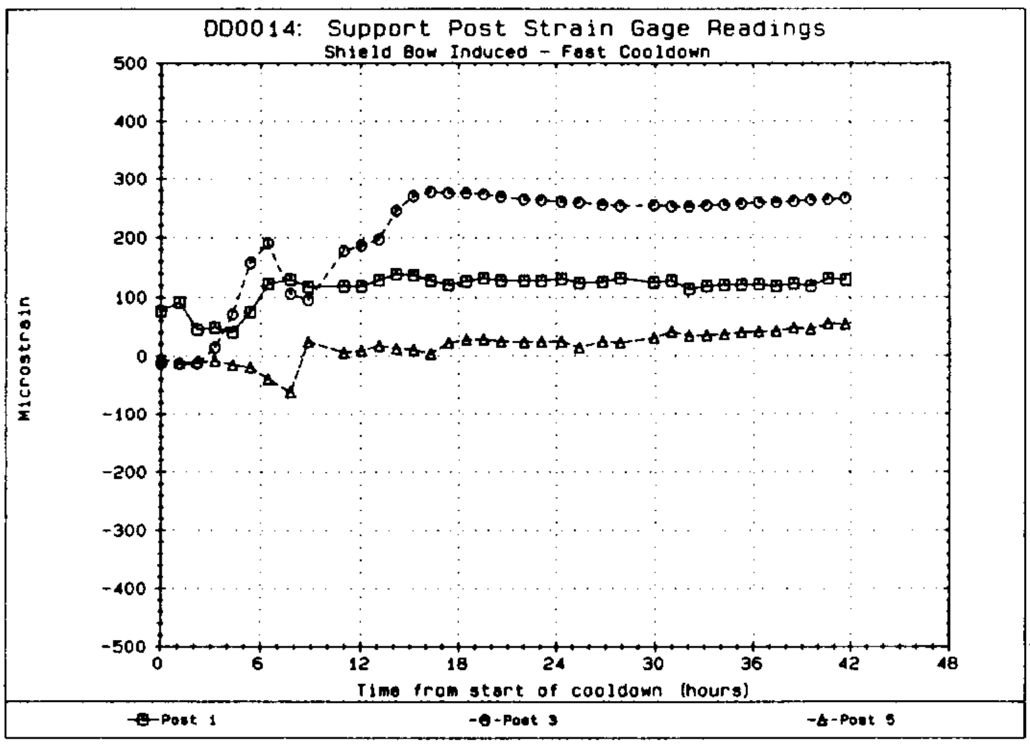

Fig. 2. Thermal bow induced support post strain gage readings

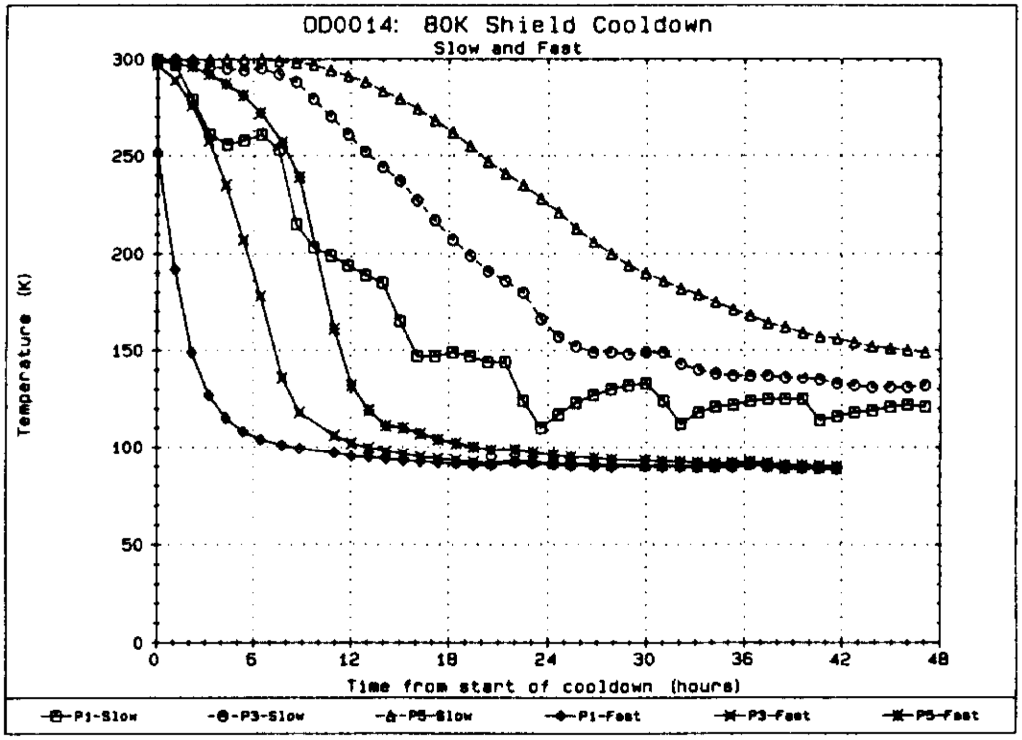

Fig. 3. 80 K shield slow and fast cooldown temperature profiles

longitudinal temperature gradients for the two cases were 70 K and 160 K respectively. Figs. 6 and 7 illustrate the corresponding bending stresses acting along the axis of the cold assembly.

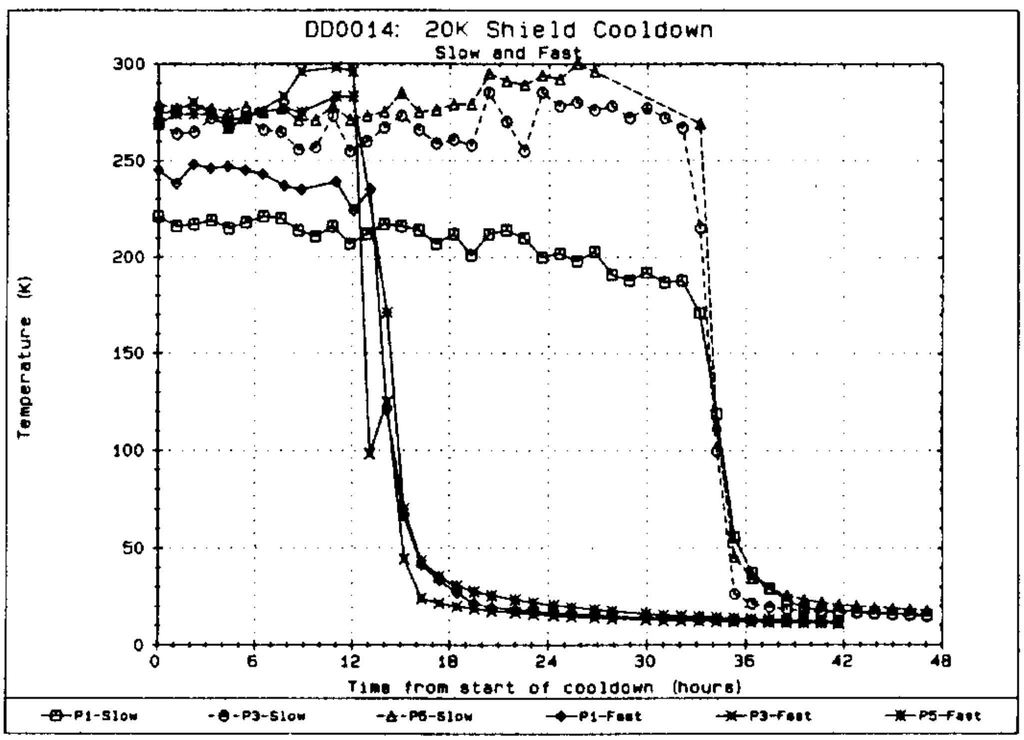

Fig. 4. 20 K shield slow and fast cooldown temperature profiles

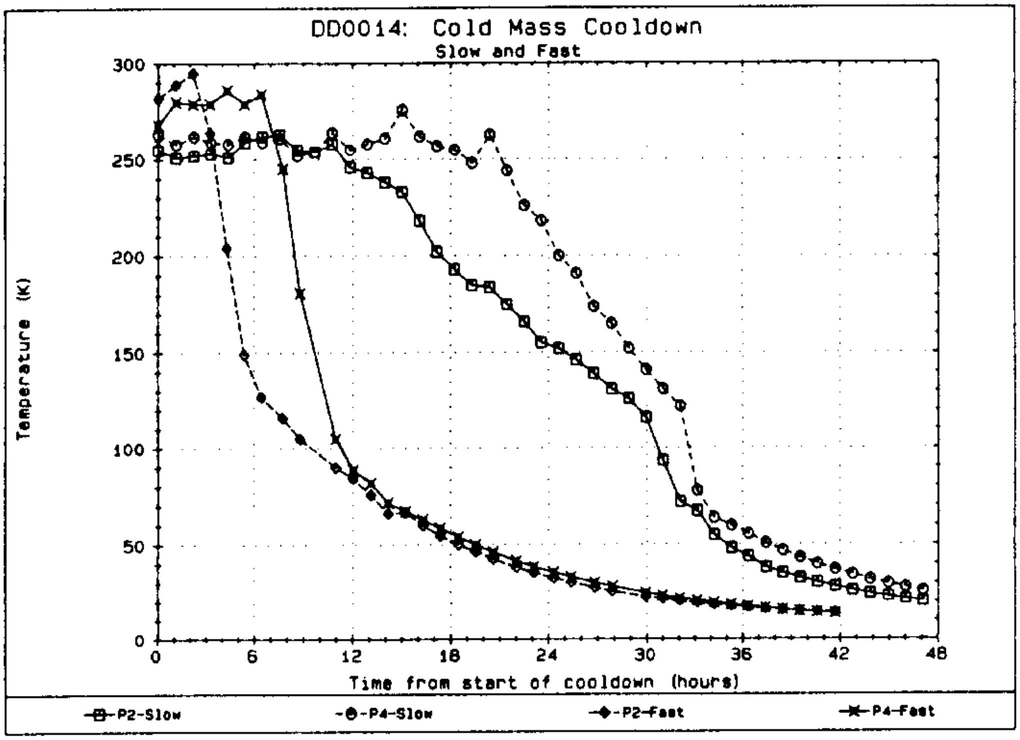

Fig. 5. Cold mass cradle slow and fast cooldown temperature profiles

The mechanism for developing bending stresses by this axial shrinkage is as follows. The warm ends of the supports are anchored to the room temperature vacuum vessel. Post spacing at assembly is 343 cm. The anchor tie bars are 305 cm long which means that 38 cm of the attachment is stainless steel. The anchor system is designed such that the tie bars grow during cooldown, the stainless steel shrinks. The net effect by design is such that at operating temperature the post

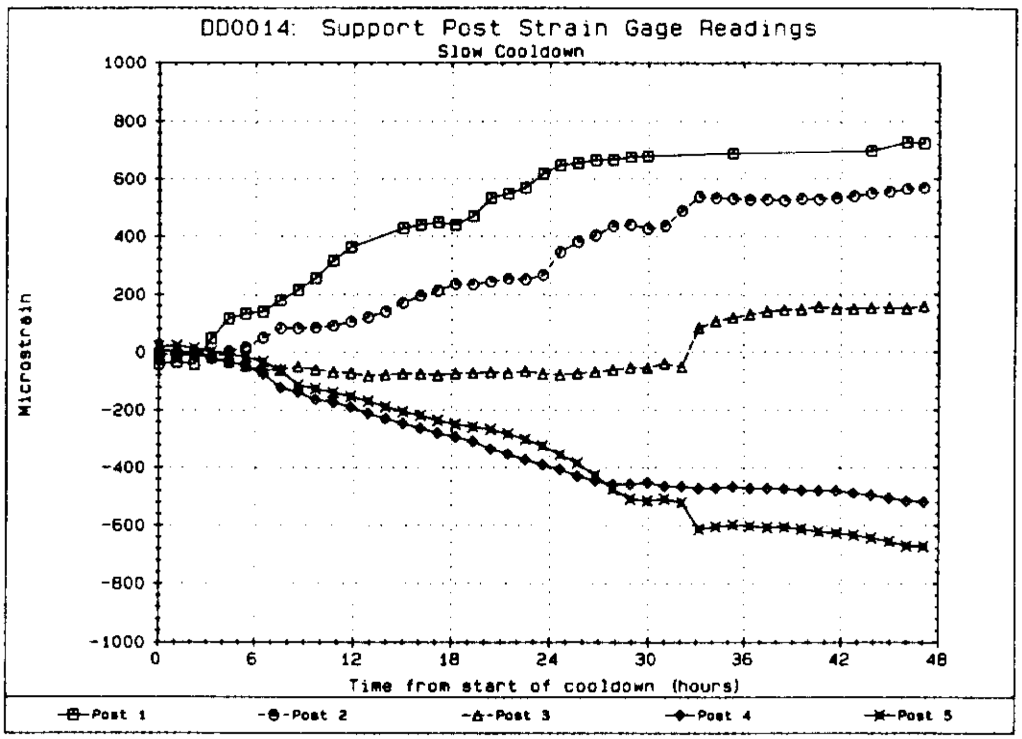

Fig. 6. Slow cooldown support post strain gage readings

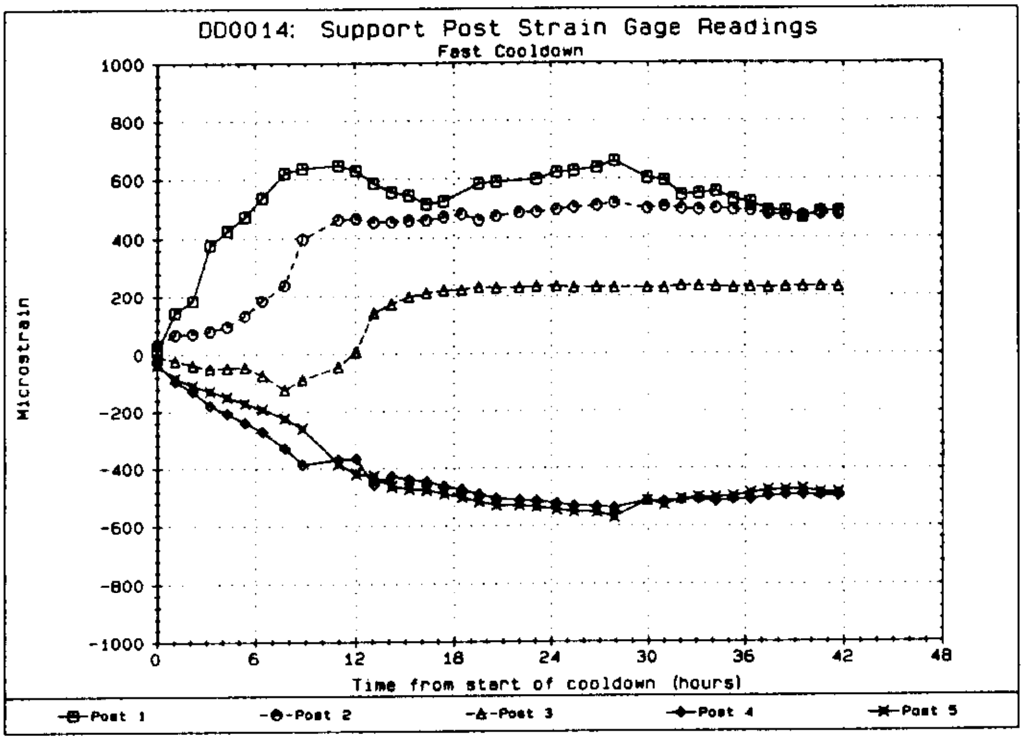

Fig. 7. Fast cooldown support post strain gage readings

spacing at the cold end is virtually identical to its as-assembled dimension. The reason we see bending stresses during cooldown is that the stainless steel end connections cool down quickly. The tie bars, on the other hand, are connected via a thermally inefficient joint and have low thermal conductivity. The result is that they cool very slowly. We should see a peak in the bending stresses in the support posts shortly after cooldown of the order shown in Figs. 6 and 7 caused by shrinkage of the stainless steel ends. As the tie bars grow, the peak should decrease.

Clearly the rate of rise in the bending loads is higher in the case of the fast cooldown, but the maximum stresses reached are virtually identical for the two cases. However, we don't see the expected decrease in strain with time. The coefficient of thermal expansion of the tie bars in DD0014 is not sufficiently high in the negative sense to offset the effects of the end fitting shrinkage so the peak stresses do not significantly diminish with time. This is a materials issue which is being addressed in subsequent tie bar material specifications. Even so, the developed stresses are low with respect to the strength of the composite tubes. Using a strain reading of 700 microstrain, the corresponding stress in the inner composite support post tube is 38.6 MPa (5600 psi). The allowable strength of the inner composite tube is 206.8 MPa (30000 psi).

QUENCH TESTS

The instrumentation on DD0014 also allowed us to monitor the behavior of the suspension system during magnet quench studies. Axial loads are induced during a quench as the result of a pressure differential across the length of the cold assembly, particularly if the quench occurs at or near the end of the coil. Early calculations indicated that the pressure differential might be as high as 2.07 MPa (300 psi) during a full field quench. Given a cross sectional area of approximately 535 cm^2 the force generated could potentially reach 111200 N. As will be illustrated below, the quench forces measured on DD0014 were significantly less than those predicted.

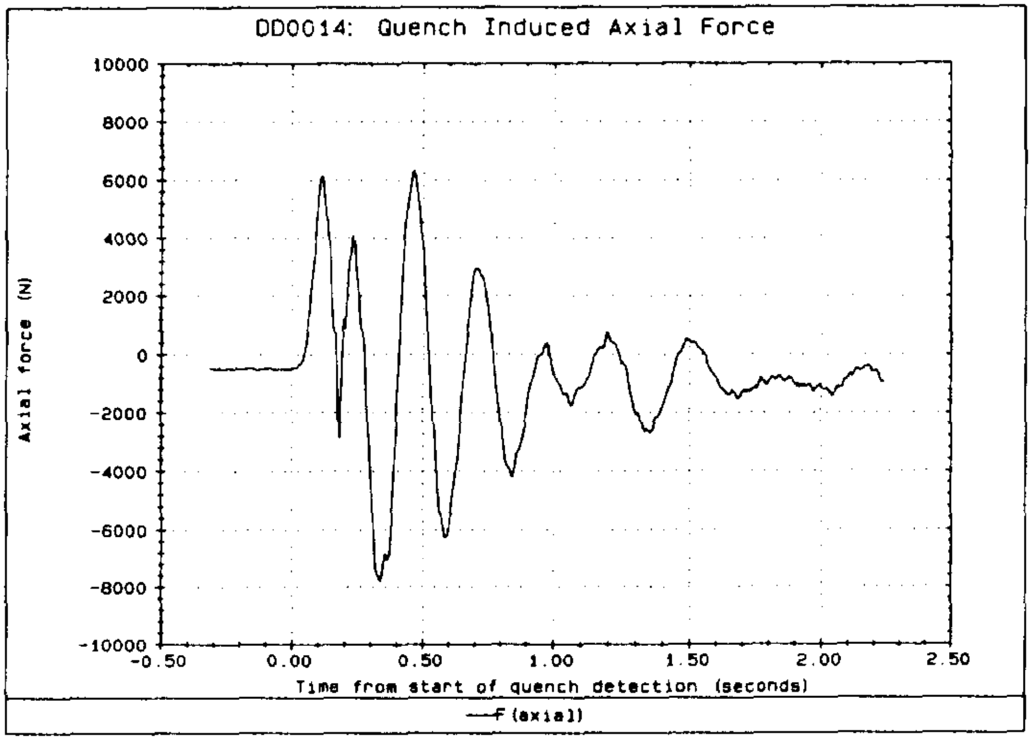

Fig. 8. Quench induced axial force

Recall that the cold assembly is only attached axially to the suspension system at the center support. The anchor tie bars serve to distribute a quench induced force to each of the remaining supports. Of interest in the test of DD0014 was a direct measure of the quench induced force and the degree to which it was distributed among all of the supports.

Fig. 8 illustrates the axial force generated during a heater induced full field quench. The heater was located at the end of the coil assembly so the referenced

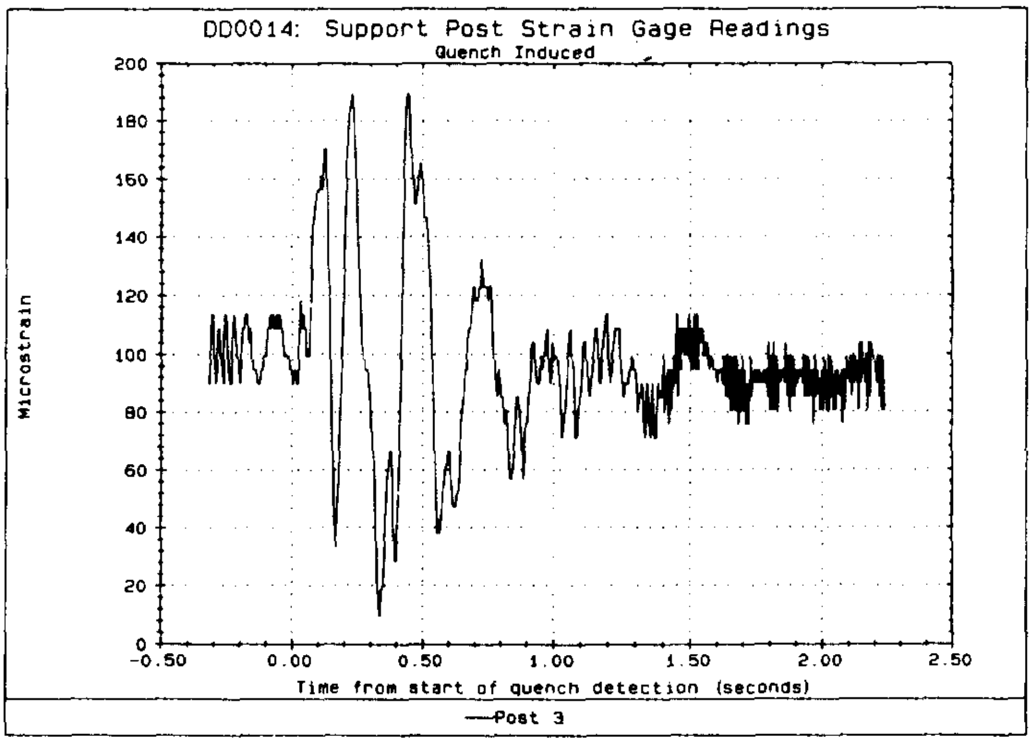

Fig. 9. Quench induced support post strain gage readings

quench should represent a worst case scenario. The force was calculated using pressure readings at extreme ends of the coil assembly and the known cross sectional area. Fig. 9 illustrates the corresponding support post strain gage readings. Using the known response of these gages to an applied static force, it is possible to calculate the force generated in each support. From that we know the load sharing characteristics of the anchor system.

Using Fig. 8 the maximum peak to peak force is 14192 N. The corresponding reactions at the supports are shown below.

Reaction at support	1,5	(end):	2852 N	(19.5%)
	2,4	(mid-span):	2871 N	(19.6%)
	3	(center):	3175 N	(21.7%)

The total force calculated using the sum of the support reactions is 14621 N which indicates good agreement between the two force determining methods. For a suspension system with five posts, 20% of the load should be seen at each support point. The above table illustrates near perfect load distribution measured on DD0014.

SUMMARY

Structurally, all of the components in DD0014 performed as predicted by the design analysis with the exception of the cooldown behavior of the anchor tie bars. The design relies on these assemblies being dimensionally stable over their operating temperature range of 300 K to 4.5 K. The results from DD0014 indicate that each assembly shrinks roughly 0.4 mm over that same range giving rise to permanent loads on the support posts. This information has been factored in to the next iteration of tie bar assemblies in an attempt to arrive at a material and fabrication method which yields the necessary properties. The tests also enabled us to lift the 100 K differential temperature constraint on cooldown rate. It appears that magnets can safely be cooled down without regard for cooldown limits.

The quench studies showed almost ideal performance of the anchor system from the standpoint of load sharing. Taken alone, they also indicated that the calculated value of the maximum force induced by a quench may have been greatly overstated. However, subsequent tests on another prototype magnet, DD0011, indicated that much higher quench induced forces are possible. Pressure readings from DD0011 showed pressure differentials as high as 1.72 MPa (250 psi).

The mechanical studies on DD0014 afforded by the additional instrumentation have been an invaluable help in confirming our performance predictions. A similar set of tests will undoubtedly be of equal help in evaluation of the next design iteration magnets.

ACKNOWLEDGEMENTS

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